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Using a novel approach to determine the pore pressure of West Qurna 15 oil well in South of Iraq

Sarah Thaier Haider *
M.sc
University of Technology,
Petroleum Technology Dept.
Baghdad, Iraq
sarhtha1994@gmail.com

Dr. Aqeel Al-Adili
Professor
University of Technology,
Petroleum Technology Dept.
Baghdad, Iraq
aqeel@uotechnology.edu.iq

Dr. Rafid Kadhim Abbas
Assistant Professor
University of AL-Qadsiyiah, College of Engineering,
Dept. of Chemical Engineering, AL-Diwaniyah, Iraq
Rafid.Abbas@qu.edu.iq

ABSTRACT

Pore pressure means the pressure of the fluid filling the pore space of formations. When pore pressure is higher than hydrostatic pressure, it is named abnormal pore pressure or overpressure. When abnormal pressure occurred leads to many severe problems such as well kick, blowout during the drilling, then, prediction of this pressure is crucially essential to reduce cost and to avoid drilling problems that happened during drilling when this pressure occurred. The purpose of this paper is the determination of pore pressure in all layers, including the three formations (Yamama, Suliay, and Gotnia) in a deep exploration oil well in West Qurna field specifically well no. WQ-15 in the south of Iraq. In this study, a new approach of mechanical specific energy (MSE) was used to predict the pore pressure of the deep well WQ-15, and compare the results obtained with the previous techniques Magara, Eaton, Equivalent Depth and Sigma log along with the actual pore pressure using a statistical equation of Absolute Average Percentage Error (AAPE). The newly suggested approach obtained is good, and accepted results of pore pressure are encouraging to be applied in other oil wells rather than depending on previous traditional methods, especially when well logs are unavailable.

Keywords: Pore pressure, Formation pressure, Specific energy, West Qurna 15 .

*Corresponding author
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استخدام محاولة جديدة لتحديد الضغط المسامي للبئر النفطي غرب القرنة 15 في جنوب العراق

سارة ثائر حيدر
ماجستير
الجامعة التكنلوجية, قسم تكنلوجيا النفط

د. عقيل شاكر العادلي
استاذ
جامعة التكنولوجية, كلية الهندسة - قسم تكنولوجية النفط

د. رافد كاظم عباس
استاذ مساعد
الجامعة القادسية , كلية الهندسية – قسم الهندسة الكيمياوية

الخلاصة

الضغط المسامي هو ضغط الموائع التي تملأ المسامات في التكوينات. عندما يكون الضغط المسامي اعلى من من الضغط الهيدروستاتيكي فهو يسمى بالضغط فوق الاعتيادي. عند تواجد الضغط فوق الاعتيادي فهو يؤدي الى حدوث مشاكل قاسية مثل الرفسة ، انفجار البئر و التي تحدث اثناء الحفر لذلك فان التنبؤ بالضغط فوق الاعتيادي هو جدا مهم لتقليل الكلفة و لتجنب مشاكل الحفر التي تحدث اثناء الحفر عند حدوث الضغط فوق الاعتيادي . الغرض من هذا البحث هو تحديد الضغط المسامي لكل الطبقات متضمنة طبقات (يمامة ، سولي و القطنية) للبئر العميق غرب القرنة 15 في جنوب العراق. في هذه الدراسة تم استخدام طريقة جديدة (الطاقة الميكانيكية النوعية) للتنبؤ بالضغط المسامي للبئر العميق WQ-15 و تم مقارنة النتائج مع الطرق السابقة (ماكارا ، ايتون ، العمق المكافئ و سيكمالوك) اضافة مع الضغط المسامي الحقيقي باستتخدام معادلة احصائية المعدل المطلق للخطأ المئوي (AAPE) . الطريقة المقترحة الجديدة استحصلت على نتائج جيدة و مقبولة و التي هي مشجعة لتطبيقها في ابار نفطية اخرى بدلا من الطرق التقليدية السابقة و خصوصا عند عدم تواجد مخططات جس الابار.

1. INTRODUCTION

Currently, the main target of any drilling operation is reducing the cost as well as avoid drilling issues or at least reduce the danger of drilling problems that might occur such as, blowouts, kick, stuck pipes, loss circulation, lost hole, and casing setting issues. West Qurna oil field is one of the largest oil fields in Iraq, with a reserve of about 43 billion barrels of crude oil. This field is located in the south-eastern part of Iraq, about 45 km north-westwards from Basra and 30 km from the Zubair oil field **(Abd Al-Razzaq, A. Dabbaj, A. and Hadi, F., 2016).**

Abnormal pressure is considered one of the issues that cause severe drilling dilemmas; therefore, predicting the pore pressure during drilling any well is significant to use the suitable drilling mud to control the well.

There are three types of pore pressure, including the following: 1-Normal pore pressure where the pore pressure gradient is very close to the hydrostatic formation pressure gradient, 2- Abnormal pore pressure where the pore pressure gradient greater or lesser than the normal pore pressure gradient. If it is abnormally high, the pressure is called overpressure, or abnormally low or subnormal, where it is called surpressure.

Pore pressure gradient is depending on many factors such as:(temperature, concentration of dissolved salt in formation water, pore fluid sort), as illustrated by (**Swarbrick and Osborne, 1998, and Louden 1972**). **(Teale, R., 1965)** presented the idea of using Mechanical Specific Energy (MSE), or it is referred to as the Specific Energy (SE), which is defined as the quantity of energy needed to destroy a unit volume of rock. However, the SE doesn't essentially represent the full energy used up in breaking the rock formation, because there are losses in hydraulic energy consumed by the drill bit while excavating the rock formation. The calculation of MES is affected by many factors such as toque (T), WOB (Weight on a bit), rotational speed, and ROP (Rate of penetration). The idea of MES used for many reasons such as

1- Assessing the performance of drilling operations 2-Evaluating the bit performance 3- studying the drilling infectiveness operations. **(Amadi WK, Iyalla I ‹2012**) MSE is used to explain the input quantity of energy employed in the drilling system. Specific Energy (SE) is studied where

laboratory tests have been performed to simulate the destruction of rock and the energy required to achieve that **(Mohan, K., Adil, F., and Samuel, R., 2015).**
(Cardona, J., 2011) was one of the researchers who used the Mechanical Specific Energy (MSE) idea to estimate the formation pore pressure rather than traditional approaches that depend on the d-exponent parameter. Cardona's model was appropriate for the case of merely strong rock environments**.**
While the specific energy way provides an easy way for suitable bits. It is well-defined as the demanded energy to remove one unit volume from the drilled rock. It can be taken any homogenous units according to **(Assi, A., 2017),** but Specific energy (SE), required energy was introduced for drilling rock volume, so this concept hasn't been considerably on rock studies as an index **(Azike-Akubue, V., Barton, S., Gee, R., and Burnet, T., 2012).**

(Majidi, R., and Last, N., 2017) suggested a methodology to determine the formation pore pressure from the combination of downhole drilling parameters as well as from *in-situ* rock properties using the concept of Drilling Efficiency (DE) and Mechanical Specific Energy (MSE). The formation pressure is believed to be a function of equivalent circulating density, MSE, uniaxial compressive strength, and angle of internal friction equation (1). The significant disadvantages of Majid's model are that there are several variables to be considered counting the petrophysical rock properties. The compressional wave velocity alone can provide an independent means of estimating the formation pore pressure. Majid's model takes no notice of the effect of hydraulic energy on the Rate of Penetration (ROP).

$$Pp= ECD-[(DE\ trend\ *MSE)-USE][\frac{1-\sin\theta}{1+\sin\theta}] \qquad (1)$$

$$USC=0.43VP^{3.2} \qquad (2)$$

$$\Theta=1.532\ VP^{\ 0.5148} \qquad (3)$$

where Pp is pore pressure, ECD is equivalent circulating density (ppg or psi/ft), DE is drilling efficiency, USE is uniaxial compressive strength, Ө is the angle of internal friction, Vp is the compressional velocity (m/s)

(Oloruntobi, O., Adedig, S., Khan, F., Chunduru, R., and Buttm S., 2018) introduced a new method to predict the pore pressure from drilling parameters. This method relied on the concept of Hydro-Mechanical Specific Energy (HMSE). The HMSE is the combination of axial, rotary, and hydraulic energies used to break and remove a unit volume of rock. Pore pressure prediction using the concept of HMSE is established on the theory that total energy consumed in breaking and removing a unit volume of rock beneath the bit. The new method can forecast the formation of pore pressure from the drilling parameters when reliable downhole measurements are missing**.**

2. THEORETICAL BACKGROUND

Historically, various approaches are used for pore pressure determination in oil wells. Three main formulas presented by **(Ben, A., Eaton, 1972, and Ben, A., Eaton, 19725)** are currently applied to quantify the formation pore pressure. The suggested three sets of equations for the determination of pore pressure are shown as follows:

Gpp= Gob - { Gob - Gnp } $[\frac{RO}{Rn}]^{1.2}$ (4)

Gpp= Gob - { Gob - Gnp } $[\frac{\Delta tn}{\Delta t}]^{3}$ (5)

Gpp= Gob - { Gob - Gnp } $[\frac{\mathrm{dco}}{\mathrm{dcn}}]^{1.2}$ (6)

where, Gpp is the predicted pore pressure gradient (psi/ft), Gob is the overburden pressure gradient (psi/ft), Gnp is the normal pressure gradient (psi/ft).
Ro is the observed resistivity (ohm.m), Rn is the resistivity from the normal trend line, Δtn is the sonic transit time at the normal trend line (μsec./ft), Δt is the observed sonic transit time (μsec./ft), dco is the observed dc exponent values, and dcn is the dc exponent values from the normal trend line.
Abnormal pressure prediction could be achieved the specific energy technique which is based on the concept that overpressure intervals that have low effective stress need less energy to excavate than the intervals that have hydrostatic pressure at the same depth.
Eaton's formula for the forecasting of pore pressure is modified depending on the concept of specific energy as follows:

Gpp= Gob - { Gob - Gnp }* $[\frac{SE0}{SEn}]^{m}$ (7)

where, SEo is the observed specific energy (psi), SEn is the specific energy from the normal trend line, and m is an exponent should be accordingly determined. The exponent (m) could be determined from the following equations*:*

Gob - Gpp= $\frac{SEo}{SEn}$ { Gob - Gnp }* $[\frac{SEo}{SEn}]$ m (8)

Log(Gob – Gpp)= Log { Gob - Gnp }+ m log [SEo /SEn] (9)

$$\frac{Log(Gob - Gpp)}{Log\{Gob - Gnp\}} = \text{m log } [\frac{SEo}{SEn}] \quad (10)$$

Plotting Log [(Gob-Gpp)/(Gob-Gnp)] vs. Log [SEo/SEn], the slope **m** could be determined.
The normal compaction trend line should be established. At normal pressure zones, the values of SE will increase with depth, whereas at high abnormal pressure intervals, the values of SE will be decreased. Eq. (7) is used to determine the formation pore pressure, where the specific energy should be determined first.
The specific energy formula was developed by **(Abbas, K., R., 2017)** depending only the hardness of the drill bit and the hardness of the rock formations being drilled as follows:

$$\text{SEo} = \frac{28137.862\ Hw}{(Hw/Ha)2.5} \quad (11)$$

where H_a is the hardness of the bit, and H_W is the hardness of the rock being excavated (N/m^2). SEn is the specific energy value extracted from the normal compaction trend line.

The calculated values of formation pore pressure from Eq. (7) should be compared with other methods as well as with the actual pore pressure obtained from the Repeated Flow Test (RFT) and from the Measurements While Drilling (MWD) logs. **(Abbas, K., R., 1996)** applied some techniques to predict the pore pressure gradient, such as (Magara, Eaton, Equivalent Depth, and Sigma log). To validate the robustness of the new suggested formula of pore pressure prediction a statistical analysis must be functioned to be used, where the determined pore pressure from the novel formula is compared to the actual formation pore pressure Absolute Average Percentage Error (AAPE) equation used for this purpose as follows:

$$\text{APPE}= [\frac{1}{N}\sum_{i=1}^{N} | \frac{A(I)m - A(I)c}{A(I)m} |] \quad (12)$$

where, AAPE is a percentage (%), $A(I)_m$ is the measured (actual) value, $A(I)_c$ is the calculated values, and N is the number of readings. This analysis can compare the calculated values for any model with the actual values where the model that has the lowest value of AAPE is the closest to the actual **(Peter, J., Huber, 1964).**

3.COLLECTION of DATA

The essential data used for the calculations in the present study were collected from the final bit record report as well as from the geological studies of West Qurna-15 deep well in the south of Iraq. The actual pore pressure is taken from the RFT and MWD logs. Data of **Table (1)** and **(2)** are quoted from the previous work of **(Abbas, K., R., 1996** and **Abbas, K., R., Hassanpour, A., Hare, C., 2014)** while the data shown in **Table(3)** is also taken from the work of **(Abbas, K., R., 1996)**.

Table 1. Data obtained from bit record, logs and geological information for WQ-15.

Depth (m)	Overburden pressure, Gob psi/ft)	Actual pore pressure, Gpp (psi/ft)	Bit commercial name	Bit type	The hardness of bit, Ha (Gpa)	The hardness of the bit, Ha of bit (N/m^2)	Formation
2935	1.033	0.4892	JD4	Milled-tooth	12.95	12950000000	Nahr Umr
3110	1.036	0.49188	JD4	Milled-tooth	12.95	12950000000	Zubair
3205	1.037	0.49235	S33	Milled-tooth	12.95	12950000000	Zubair
3890	1.039	0.67548	FS5 KJ	Milled-tooth	12.95	12950000000	Sulaiy
4025	1.043	0.76544	J33	Insert	15	15000000000	Sulaiy
4085	1.044	0.76623	J33	Insert	15	15000000000	Sulaiy
4125	1.045	0.793256	J3	Milled-tooth	12.95	12950000000	Gotnia
4140	1.047	0.81404	J33	Insert	15	15000000000	Gotnia
4255	1.0488	1.011488	J3	Milled-tooth	12.95	12950000000	Gotnia
4286	1.047	0.9824	J3	Milled-tooth	12.95	12950000000	Gotnia

4304	1.048	1.0108	J3	Milled-tooth	12.95	12950000000	Gotnia
4360	1.048	0.99763	J3	Milled-	12.95	12950000000	Gotnia
4368	1.047	0.9957	J33	Insert	15	15000000000	Gotnia
4375	1.048	0.99476	F4	Insert	15	15000000000	Gotnia
4390	1.049	0.9907	F4	Insert	15	15000000000	Gotnia
4368	1.047	0.9957	J33	Insert	15	15000000000	Gotnia

Table 2. Main rock formations being penetrated in WQ-15 with the corresponding .

Rock formation	**Hardness (Gpa)**
Sandstone	10.79
Limestone	1.079
Dolomite	2.45
Shale	1.961
Anhydrite	1.569
Conglomerate	1.17

Table 3. Pore pressure obtained from various methods of Eaton, Magara, Equivalent depth and sigma log for WQ-5.

Depth (m)	Pore pressure from Eaton (GPC1), psi	Pore pressure from Magara GPC2), psi	Pore pressure from Equivalent Depth (GPC3), psi	Pore pressure from Sigmalog (GPC4), psi
2935	0.47754	0.49885	0.49573	0.770198
2992	0.4464	0.47578	0.47881	0.440147
3110	0.562178	0.466	0.47704	0.4804776
3201	0.54348	0.5447	0.53629	0.4842357
3205	0.53427	0.53617	0.53095	0.4822636
3575	0.6817	0.5739	0.57169	0.59941
3710	0.69545	0.583776	0.578887	0.5988495
3874	0.57393	0.5815	0.579758	0.714267
3890	0.75908	0.5854	0.7588	0.7959568
3915	0.765276	0.7726	0.7943	0.8117358
3940	0.79865	0.7699	0.794209	0.8300221
4025	0.7621	0.76135	0.7842218	0.8149517
4050	0.760484	0.76928	0.7882	0.8147386
4085	0.73834	0.7845	0.80392	0.7954028
4115	0.81566	0.7834	0.80538	0.8417547
4125	0.8051004	0.80308	0.82742	0.838145
4140	0.84723	0.79813	0.821018	0.8854011
4211	1.010074	0.99307	0.99166	0.9783616
4255	1.00831	1.00843	0.99899	0.9750899

4268	1.00446	1.00272	0.99481	0.9683444
4286	1.00043	1.005229	0.99631	0.9588544
4291	0.999823	1.0006	0.99555	0.9568824
4304	1.009107	1.00905	0.99793	0.972255
4325	1.017033	1.00946	0.99806	0.9845696
4360	1.0065	0.99799	0.9776	0.970382
4368	1.01019	0.997	0.9778	0.958297
4375	1.005119	0.9826	0.979067	0.9404565
4390	1.02047	0.9899	0.98439	0.9641977
4395	1.00449	0.981815	0.97887	0.9380187
4400	0.89497	0.78316	0.80227	0.9535768
4413	0.88502	0.88502	0.83704	0.94684
4431	0.88686	0.88686	0.87291	0.9414758
4439	0.89576	0.89576	0.83918	0.945141
4526	0.89185	0.89185	0.8199	0.440612
4550	0.888272	0.888272	0.81334	0.9421071

4. METHODOLOGY

1- The first step is to calculate the values of the observed specific energy (SEo) from Eq. (11). The results are shown in **Table (4)**.
2- A normal compaction trend line is drawn to extract the values of the normal specific energy (SEn) that decreases gradually with depth. The results are displayed in **Table (4)** and **Fig. (1).**
3- Computation of the exponent (m) is achieved by drawing Log [(Gob-Gpp)/(Gob-Gnp)] vs. Log [SEo/SEn] and then plotting the best line through the points by Excel, where the slope of the best line is (m). The slope was found to be 1.043. **Fig. (2)** shows the plot and the best line through the points.
4- Eq. (7) was used to calculate the pore formation pressure (Gpp) based on specific energy. The produced results are demonstrated in **Table (5)**.
5- Plotting the pore pressure (Gpp) obtained from **Eq. (7)** along the actual pore pressure taken from well logs versus depth. This plot is shown in **Fig. (3)**.
6- The Absolute Percentage Error (AAPE) was calculated from Eq. (12) for the new model based on (SE) and also for all the previous techniques being used to predict the pore pressure for WQ-15 i.e. Magara, Eaton, Equivalent Depth and Sigma log, where this statistical equation compares between the measured and the calculated values to reveal the robustness of the model that is closest to the measured or actual values.
7- Plotting the pore pressure obtained from Magara, Eaton, Equivalent Depth, and Sigma log methods as well as the newly developed approach with actual pore pressure taken from RFT and MWD logs versus depth. This plot is illustrated in **Fig. (4).**

5. RESULTS and DISCUSSION

The plot of SE (Specific Energy) obtained from the new model versus depth is displayed in **Fig. (1)**. The SE values are computed from Eq. (11). In this well, the specific energy is affected by the hardness of the rock formation as well as the hardness of the bit that excavates the well. The normal compaction trend line (NTC) is drawn for the values of SE been decreasing gradually from 2895 m to 3895 m, whereas SE decreases with depth, while below 3895 m, i.e., top of overpressure zone, the specific energy starts to undergo departure from NTC to lower values. This is attributed to the occurrence of subsurface overpressure conditions. In this formation, the amount of rock compaction is reduced, leading to an increase in pore pressure and decreases specific energy that is required to remove the unit volume of rock. **Fig. (2)** shows the determination of the exponent (m) in Eq. (11). **Fig. (2)** illustrates that the value of (m) produced was log11.063, which means m = 1.043. **Fig. (3)** displays the plot of the pore pressure resulted from the new suggested formula with the actual pore pressure versus depth. The actual pore pressure measurements were taken from MWD and RFT logs. It is worth mentioning that pore pressure values produced from the new approach are close to the actual in-situ pore pressure.

Fig. (4) displays a comparison between pore pressure obtained from previous approaches with the novel method along with actual formation pressure versus depth. Previous methods are Eaton GPC1), Magara (GPC2), Equivalent Depth (GPC3), and Sigma log (GPC4). The Results of the pore pressure obtained from previous methods are demonstrated in **Table (3)**, while the results of the new method (dependent on specific energy) are displayed in **Table (5)**. A statistical analysis using the implication of AAPE (Absolute Average Percentage Error) is applied to clarify the degree of convergence of each method with the actual pore pressure. APPE is calculated from Eq. (12). This equation is used to compare measured values with the calculated ones for any model. Therefore, the model that has the lowest APPE is considered the best among the models. Results of APPE for the previous techniques were (3.811%, 3.9104 %, 2.1348 %, 3.0935 %, and 5.628 %), referring to the new model based on SE, Eaton, Magara, Equivalent Depth, and Sigma log respectively. Although, from the APPE values, it is shown that the new approach for pore pressure determination is considered a good and reliable approach as it has very low AAPE, i.e., 3.811 % compared with other methods. On the other hand, the pore pressure gradient calculated by Sigma log is the worst, according to APPE. The abnormal pore pressure in well WQ15 is found to be in Yamama, Suliay, and Gotania formations as concluded by **(Abbas, K., R., 1996)**.

Pore pressure gradient calculated by the method presented in this research is considered a good approach to predict pore pressure in case of the unavailability of well logs.

Table 4. Results of observed and normal specific energy.

Depth (m)	Observed specific energy (SEo), Mpsi	Normal specific energy (SEn), Mpsi
2935	SE observed (Mpsi)	170340
2992	175328.1578	169070
3110	159083.7719	156310
3201	159083.7719	151270
3205	159083.7719	151280
3874	138186.9306	102960
3890	78382.59484	101690
3915	65086.52311	102950
4025	65501.65226	92800
4050	46525.74901	88980
4085	42271.34747	86440
4115	42545.96323	83896
4125	61235.97021	82625
4140	61037.93305	82610
4211	43657.18112	80085
4255	8265.537429	73728.8
4268	3572.407604	72440
4286	3078.003329	72470
4291	14766.59663	72460
4304	4727.465597	72450
4325	7800.924068	69920
4360	8749.587679	67370
4368	13447.13414	66110
4375	10226.49205	66100
4390	13532.99923	64830
4395	3499.681255	63559
4400	24116.83674	66101.69
4413	30085.29073	63560
4431	26983.33134	61020
4439	26002.22041	61010
4526	27990.60357	55932
4550	26002.22041	53380

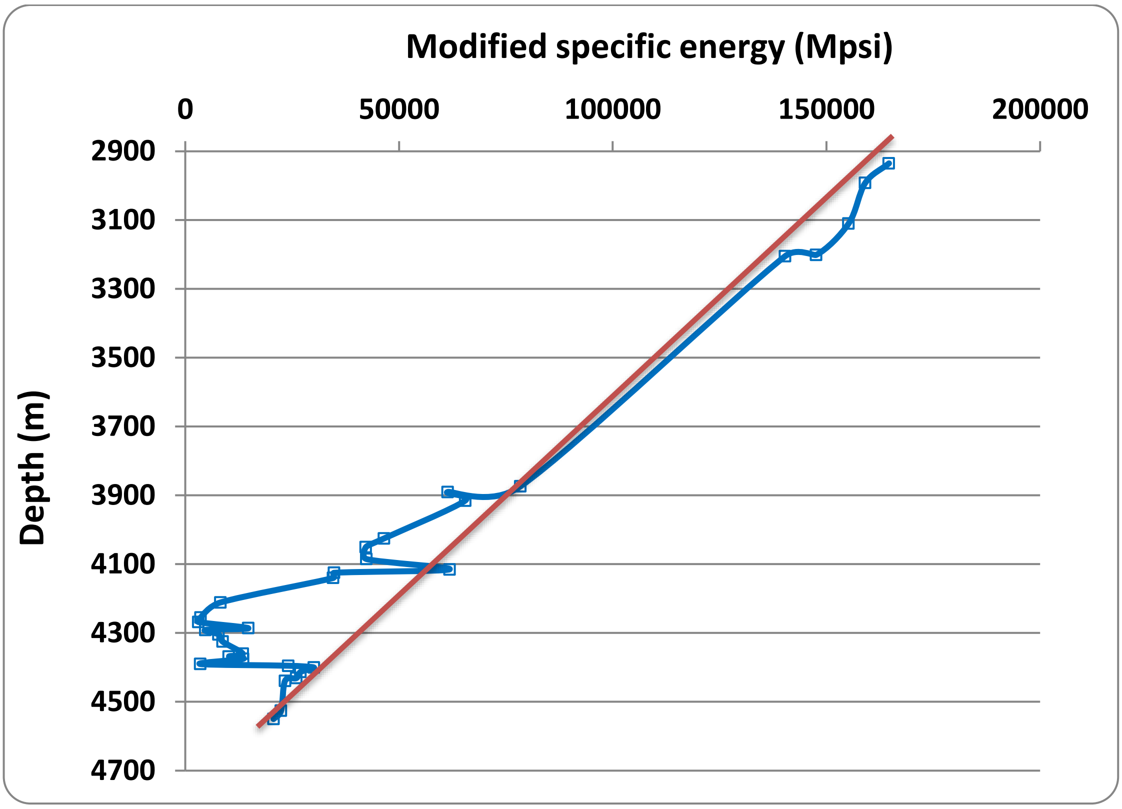

Figure1. Specific energy obtained from the new formula versus depth.

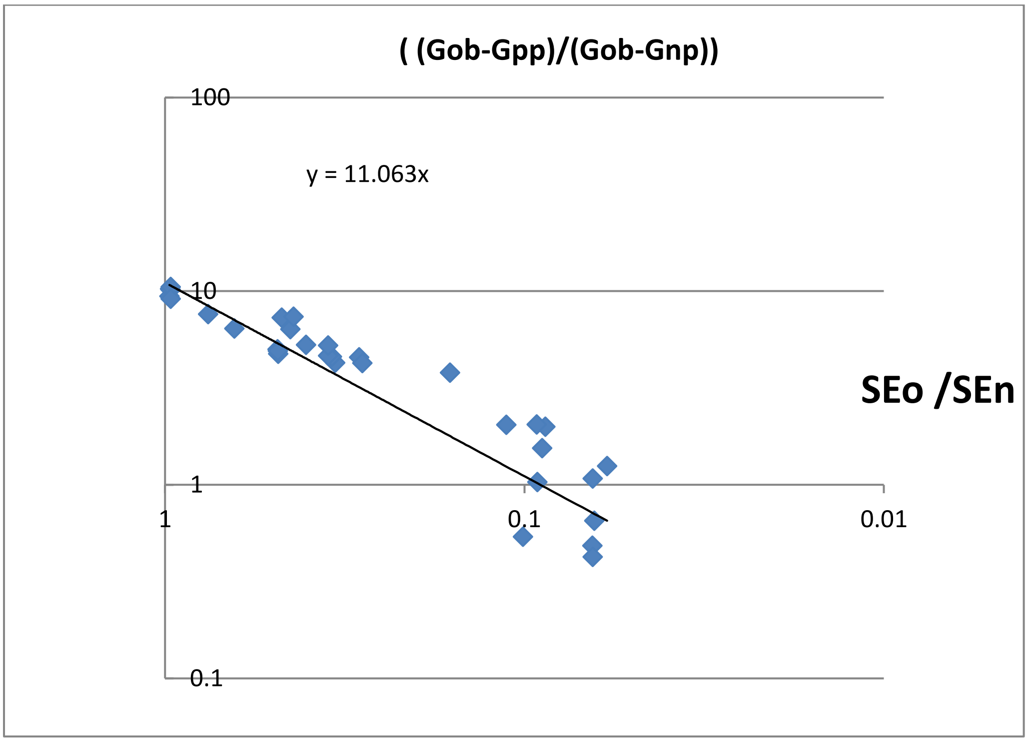

Figure 2. Log [(Gob-Gpp)/(Gob-Gnp)] versus Log [SEo/SEn].

Table 5. Results of pore pressure depended on specific energy.

Depth (m)	Pore pressure gradient predicated
2935	0.492667218
2992	0.508698625
3110	0.476428006
3201	0.486987105
3205	0.516955973
3874	0.619316321
3890	0.713799056
3915	0.695072302
4025	0.776396101
4050	0.792334882
4085	0.783235032
4115	0.63576808
4125	0.824082437
4140	0.826788259
4211	1.00004279
4255	1.028344694
4268	1.028389191
4286	0.947560144
4291	1.01963841
4304	0.998712085
4325	0.989823289
4360	0.950628357
4368	0.973622882
4375	0.947861971
4390	1.025947209
4395	0.85153643
4400	0.80743737
4413	0.825365111
4431	0.82443513
4439	0.850417695
4526	0.841076778
4550	0.849291995

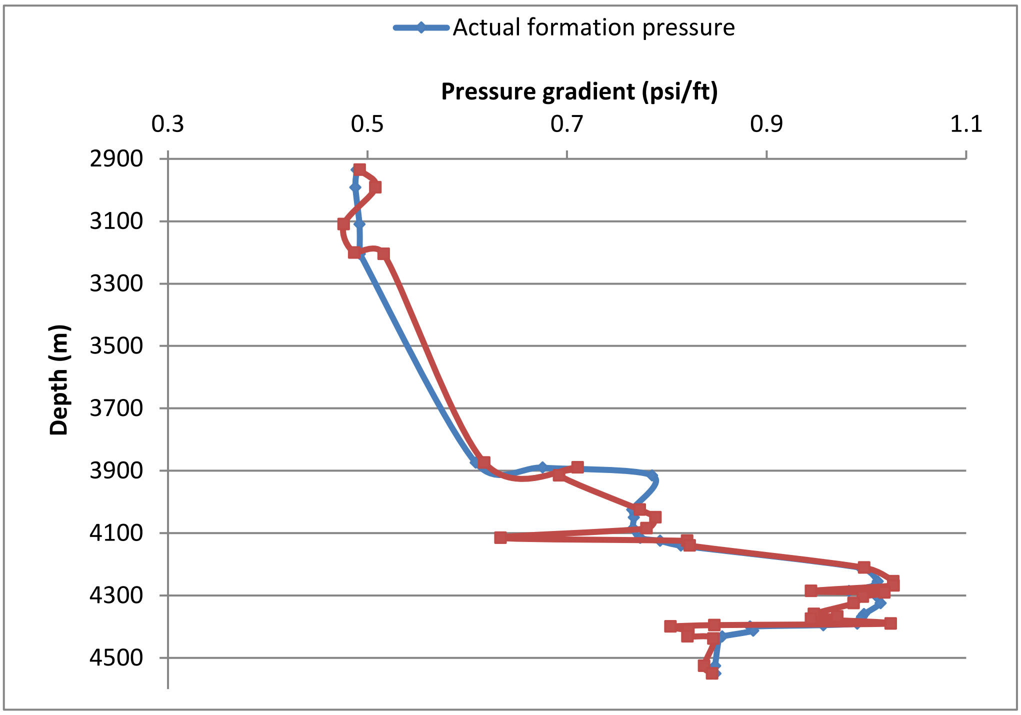

Figure 3. Pore pressure predicated by SE method with actual pore pressure vs. depth.

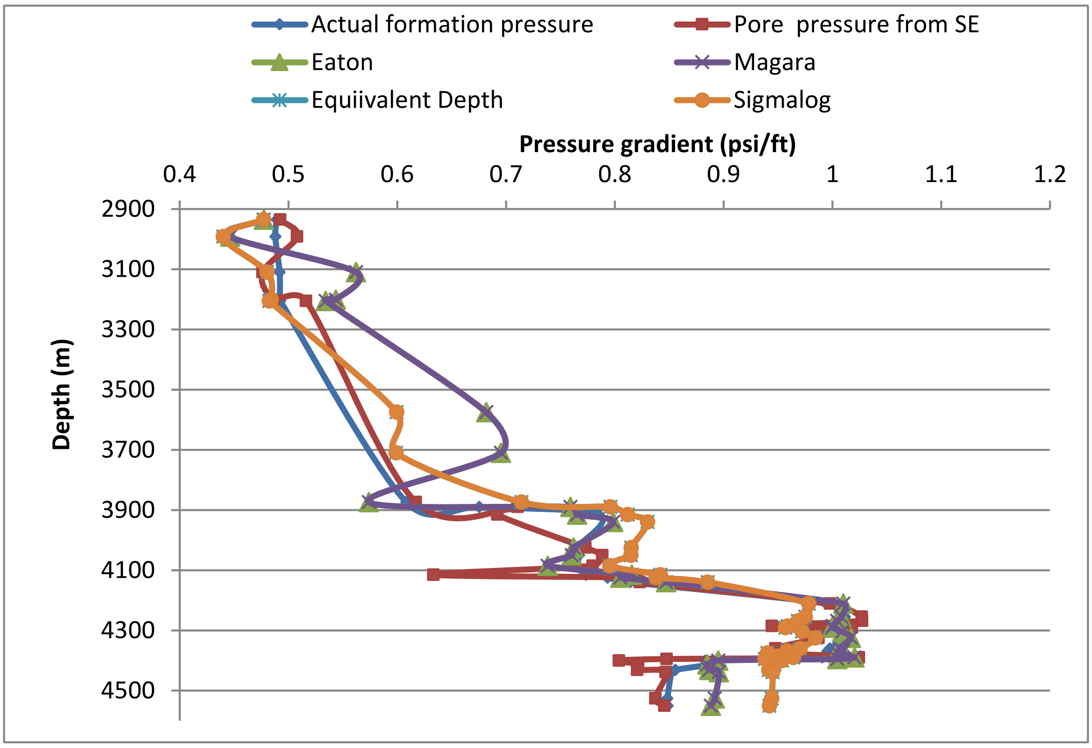

Figure 4. Comparison of various methods of pore pressure determination along with the actual pore pressure versus depth.

CONCLUSIONS

1-Specific energy technique is concluded to be a good and acceptable approach to estimate pore pressure gradient, especially when well logs are unavailable.
2- From the results, the new approach was found to be close to the actual pore pressure as the percentage error is logically acceptable.
3- It is possible to calculate the SE values from other equations found by Teale and Rabia. The previous equations depended on the drilling parameters, whereas the equation used in the present research depends only on the hardness of the rock formation and the hardness of the drill bit.

NOMENCLATURE

ECD equivalent circulating density (ppg or psi/ft)
DE Drilling Efficiency
USE uniaxial compressive strength
Ө angle of internal friction
Vp compressional velocity (m/s)
NTC normal compaction Trend line
Dc ?/cor///r/ected d – exponent
Dcn dc ‐ exp//onent from the normal compaction trend at a given depth
Dco computed dc ‐ exponent from the measured data at a given depth
M HMSE exponent
MWD measurement while drilling
RFT repeated Flow test
MES mechanical specific energy(psi)
HMSE hydro-mechanical specific energy (psi)
APPE absolute Average percentage error
Gnp normal pore pressure gradient at a given depth (psi/ft)
Gob overburden pressure gradient at a given depth (psi/ft)
Gpp pore pressure gradient at a given depth (psi/ft)
Hw hardness of bit
Ha hardness of rock formation
SEo specific energy observed
SEn normal Specific energy
GPC1 pore pressure gradient (Eaton method) psi/ft
GPC2 pore pressure gradient (Maraga method) psi/ft
GPC3 pore pressure gradient (Equivalent Depth Method) psi/ft
A(I)m measured values(actual value)
A(I)c calculated value
APPE absolute Average Percent Error
N number of values
Ro observed shale resistivity at a given depth (ohm – m)
Rn normal compaction trend shale resistivity at a given depth(ohm – m)
ROP rate of penetration (ft/hr)
T torsion or torque (lb-ft)
∆tn normal compaction shale travel time at a given depth (microsecond –ft)
∆to observed shale travel time at a given depth (micro-second/ft)

Pp pore pressure

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